

Title:

**Island and Ship Trail Clouds: the Rosetta Stone
of Clouds, Pollution, and Climate?**

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Island and Ship Trail Clouds: the Rosetta Stone of Clouds, Pollution, and Climate?

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ABSTRACT:

Cloud/Climate Feedback is a combination of words known to be important but extremely difficult to quantify or even assign a direction. A 4 % increase in boundary layer clouds would cool the earth as much as a doubling of CO₂ would warm it (Randall *et al*, 1984). Studies have shown that warmer sea surface temperatures are associated with fewer clouds (Oreopoulos and Davies, 1992). We do not know how much of this effect is due to direct solar warming of surface water in the absence of clouds. We also know there are more eastern ocean marine boundary layer clouds in summer than winter. Do warmer sea surface temperatures or more summer-like conditions best represent global warming? Twomey, 1974 has proposed that increasing aerosol pollution would lead to brighter clouds (indirect aerosol effect). This relationship does have determined sign (i.e. cooling) but is very difficult to quantify. Cloud trails from ships and islands hold the potential of addressing Cloud/Climate Feedback by observing atmospheric response to large perturbations in turbulence and aerosol. However, before cloud trails can be used as a Rosetta Stone connecting pollution and climate, much more needs to be understood about the micro- and macrophysics of cloud trails.

INTRODUCTION:

Los Alamos National Laboratory has helped the DOE Atmospheric Radiation Measurement (ARM) Program for about ten years. The major part of this work is to help operate three sites in the Tropical Western Pacific (TWP). These sites include Manus, Papua New Guinea, Nauru, and Darwin, Australia. From 1990 to 1995 we were also part of a DOE Quantitative Links to Climate Program studying ship trail clouds from ships off the California Coast. The focus of these studies is to improve climate models (mainly through their many parameterizations). One of the most important parameterizations in climate models is related to how clouds respond to small changes in global solar radiation affected directly and indirectly by anthropogenic gases and aerosol. Ocean boundary layer clouds are about 50 times as effective in affecting surface temperatures as CO₂. It is difficult to estimate how much less is understood about how clouds respond to radiative effects and aerosol than the effect of increased CO₂ on surface temperatures in a cloudless sky, but our ignorance is substantial. I will concentrate in this paper on uncertainties associated with boundary layer clouds. However, the uncertainties associated with cirrus clouds and their relationship to tropical precipitation (Linzen, 1990) and tropical warm pool convection (Ramanathan *et al*, 1989) may be as important or more important. All of these uncertainties fall under the broad category of Cloud/Climate feedback.

The process that could be used to determine Cloud/Climate feedback from years of data from ARM sites (TWP, North Slope of Alaska, and Southern Great Plains) seems straight forward, at first. We could just compare cloud coverage, frequency, cloud bottom and top heights to the surface temperature for different seasons of the year. However, these comparisons may be meaningless outside of the context of all the parameters of global climate change (i.e. not just surface temperatures). What seems a useful result such as "warmer surface temperatures are associated with fewer clouds" becomes a trivial result when phrased as "the sun warms the surface when there aren't clouds in the way". Further complicating these comparisons is the separation of small changes in climatological parameters (signal) from highly variable and difficult to measure controlling parameters such as clouds, water vapor, and vertical motion (noise).

The following are some cloud/climate conundrums associated with boundary layer cloud/climate feedback:

- Why are daytime/nighttime temperature differences decreasing (Karl *et al*, 1984)?

- Why don't satellite and rawinsonde temperatures show a warming over last 20 years (Pielke et al, 1998)?
- How can ocean clouds response to global warming using measurements be interpreted?
- What effect on clouds can be expected from pollution aerosols (Twomey, 1974)?

Our efforts at LANL to try to understand the response of marine boundary layer clouds to perturbations associated with ship trail clouds began as a result of meeting with Shawn Twomey in 1986. He described how useful ship trail clouds could be and how difficult it is to associate a specific ship trail cloud to a specific ship. This conversation reminded the author of the existence of one of the most detailed and highest resolution image of ship trail clouds. This image was taken from a photograph from an Appollo-Soyuz satellite mission in 1975 (Figure 1). The cloud-free regions on the sides of the cloud trails and the fact that the clouds were not noticeably brighter at the intersection of the ship trails indicated that cloud dynamic effects were important at least in this instance. An ocean cloud model was applied to this problem by Jim Kao at LANL. His model results showed that the heat output from a large ship (on the order of 10 MW) could reproduce at least some of the features observed (Porch and Kao, 1996). In order to separate aerosol CCN effects and cloud dynamic effects we participated in two ocean experiments. The first experiment was in 1991 where we observed the effect of ships and a total solar eclipse on marine boundary layer clouds (Porch *et al*, 1995). The second experiment was conducted as a participant in the Monterey Area Ship Track (MAST) experiment (Porch *et al*, 1999).

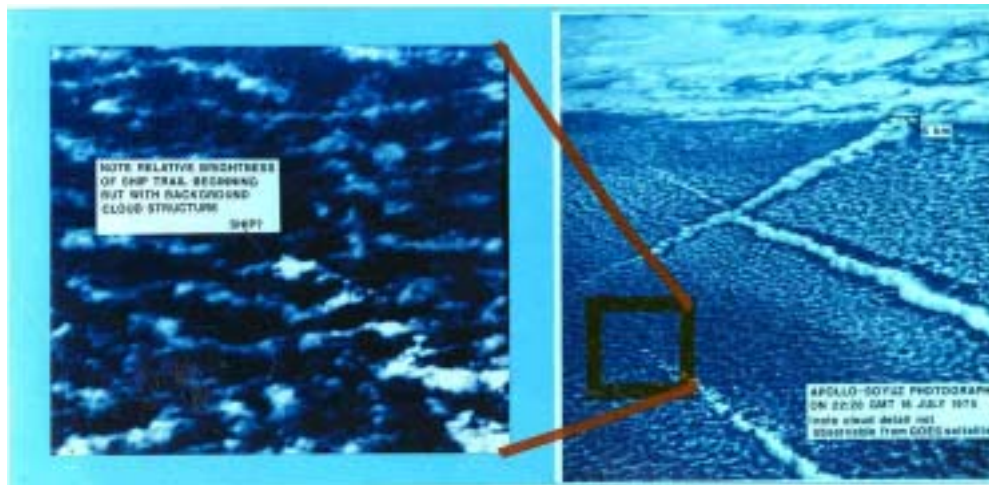


Fig. 1 Apollo-Soyuz Photo Showing Formation of Ship Trail Clouds and Cloud Free Regions on Cloud Trail Sides as Ship Trail Develops

SEAHUNT 1991:

A ship-based experiment on the research vessel *Egabrag* to study ship tracks and other external forcing on marine boundary-layer clouds called SEAHUNT (Ship-Track Evolution Above High Updraft Naval Targets) was performed in June 1991 off the coast of southern California and northern Mexico (Porch *et al*, 1995). This experiment documented the first surface observation of a ship-track cloud that was known to be a ship-track cloud simultaneously observed by satellite.

Separate aspects of this experiment are described in Hindman *et al*, 1994 and Hudson *et al*, 1992. The major ship trail observed persisted for only one day (Figure 2). The background cloud form within which we encountered this ship-trail cloud on 13 July was low-level patchy surface fog. This cloud form was associated with extremely low surface concentrations of CCN. We encountered four ship trails at night (three on the night of 12-13 July and one on

the night of 24-25 July). A very prominent and defined ship trail was observed about 11:00 PDT on 13 July. Heavy drizzle was observed the preceding day and night. Although it may not be clear in the reproduction of Figure 2, a small ship trail was associated with our research vessel (black and white insert). This is surprising given the small heat and CCN release rate from our ship. Figure 3 shows images taken from the *Egabrag* as it entered and exited the ship trail cloud.

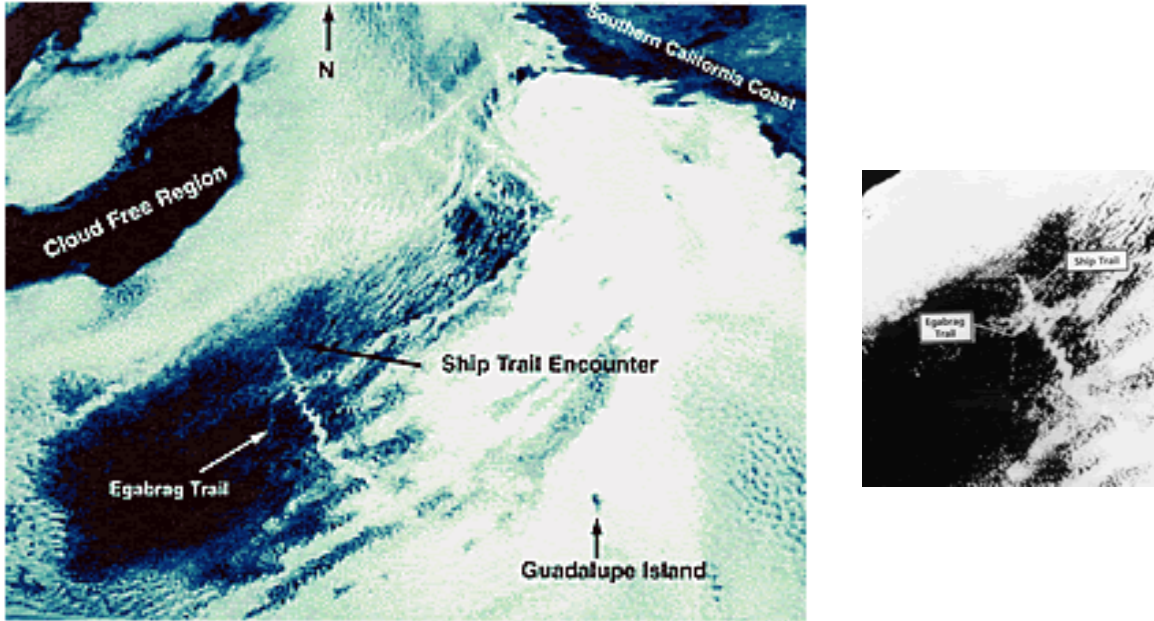


Fig. 2 Ship Trail Encounter in June 1991 on *RV Egabrag* southwest of San Diego

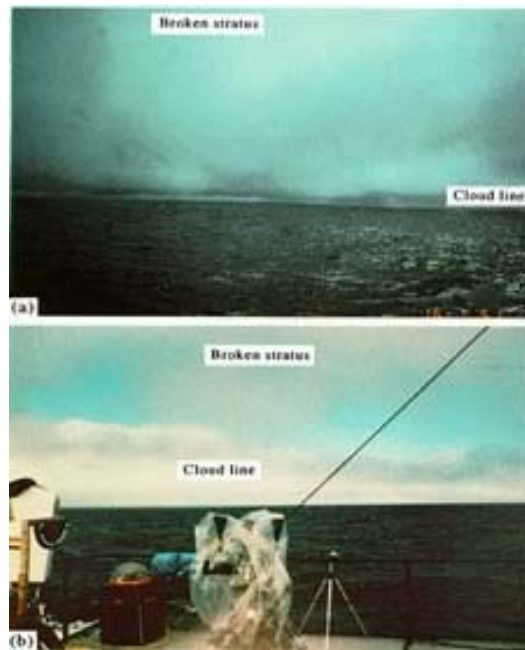


Fig. 3 Photographs taken from the *Egabrag* as we passed under the Ship Trail shown in Fig. 2

Also surprising is the wavelength dependence of this feature in the satellite imagery. As Coakley *et al*, 1987 point out, AVHRR channel 3 permits observation of ship trails that cannot be seen at visible wavelengths. The ship trail produced by our research vessel can be observed in the visible wavelength channels of GOES and AVHRR satellite images, but is not readily detectable on the channel 3 AVHRR image. Since channel 3 is very sensitive to droplet size, this seems to imply that though the ship appears to have increased the cloud liquid water in clouds in its wake, the clouds in the trail do not appear to have significantly different cloud droplet sizes. This is expected in low CCN environments since the channel 3 reflectance/droplet size relationship is flat at large droplet sizes (12-15 μm radius). The fact that the trail observed was our own and no droplet spectral measurements were made during this experiment means that we could not independently verify the lack of size differences suggested by the satellite. Visual observations of fogbows during this time showed a lack of color separation consistent with larger droplets (Lynch and Schwartz, 1991).

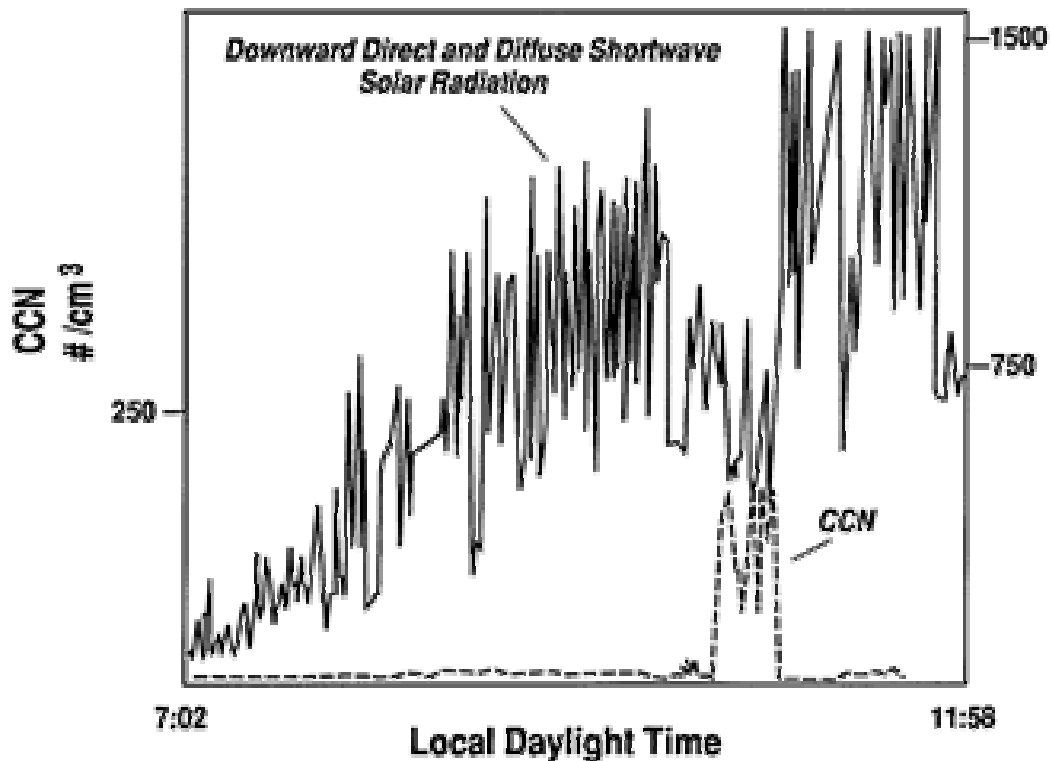


Fig. 4 Plot of CCN concentrations and solar radiation versus time showing a peak in CCN associated with the Ship Trail Cloud encounter shown in Fig. 2

The CCN levels increased beneath the ship trail (Figure 4) to levels about a factor of two higher than mean levels observed below fully developed marine stratus clouds encountered about an hour later. The low CCN levels observed on this day were necessary for unique discrimination of the ship trail from shipboard observations. Visual observations from the ship indicated that the ship-trail cloud top was higher than the background cloud tops. This was done by observing photographs of the trail as background clouds passed between our ship and the ship trail. Cloud free regions were also observed on both sides of the ship trail from our ship and from GOES satellite imagery. The cloud free region was much more extensive on the upwind (about 1.5 km) than downwind side of the ship trail. The cloud-free region on the upwind side of the ship trail is seen as an increase in the solar radiation in Figure 3. The clear region on the downwind side was shadowed by the ship-trail cloud and is not distinct in the solar radiation record. The existence of these cloud free regions implies that there was a strong cloud dynamic effect. Porch *et al*, 1990 proposed the possible importance of cloud dynamic effects on ship-trail formation was proposed by. Recent support for this hypothesis has come from analysis of features generated by islands in the California current (Figure 5) that appear identical to ship trails in satellite images (Dorman, 1994).

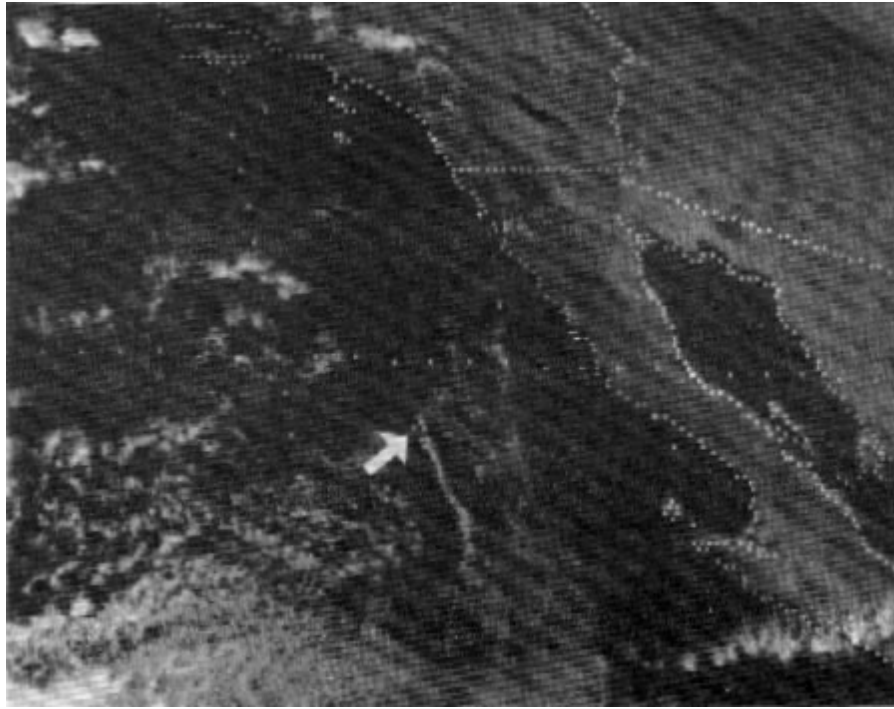
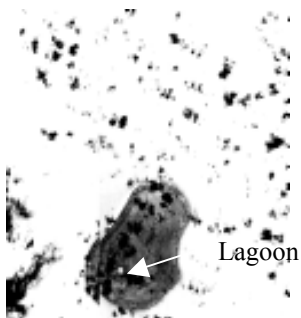


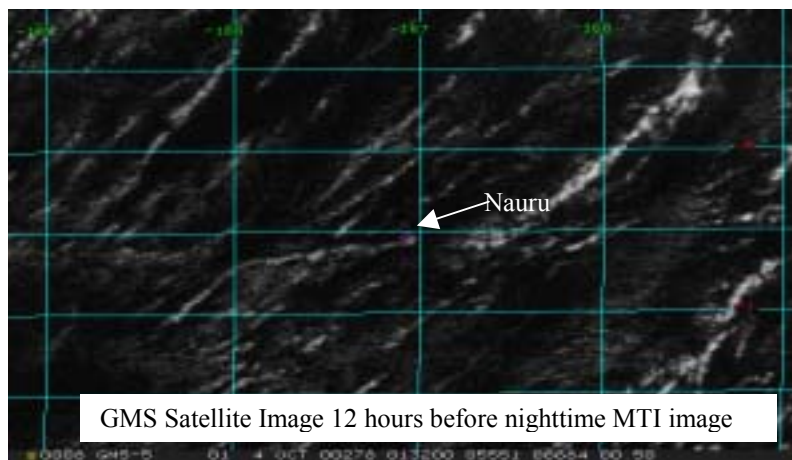
Fig. 5 Island cloud trail formed by Guadalupe Island (Mexico)

NAURU ISLAND CLOUD TRAILS:

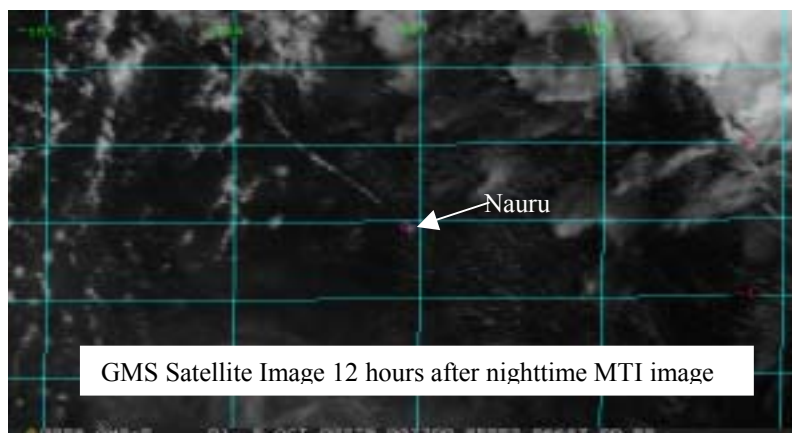
Our group at LANL helped in the first DOE ARM Intensive Operation Period (IOP) in the tropics called Nauru99 (Yoneyama, 2000). This experiment compared ship-board measurements from the NOAA Research Vessel *Ron Brown* and the Japanese Vessel *Mari* with the ARM Cloud and Radiation Test bed (CART) site on the island of Nauru and the NOAA research buoy network closest to Nauru. The observation of a persistent island cloud trail during this experiment stimulated an analysis of GMS satellite images over Nauru (Nordeen *et al*, 2001). About 9 months after the Nauru99 study, the DOE Multispectral Thermal Imaging (MTI) satellite was successfully launched. LANL is one of the major groups analyzing and disseminating the MTI data. Figures 6 and 7 show examples of comparisons between GMS and MTI images. The longitude lines on the GMS images are separated by 1 degree (about 111 km). The island of Nauru in the MTI images is 4 to 5 km wide. Figure 6 shows a nighttime image that indicates there may be a cloud trail forming. GMS images 12 hours before and 12 hours after the MTI image show a cloud trail direction change that seems to indicate that the island cloud trail existed through the night. The presence of an island cloud trail at night is important in separating the effect of turbulence generated by the physical interception of the wind by the 40 m altitude island and the turbulence generated because the island generates convective heat during the day. Figure 7 shows that the wind direction measured at the CART site on Nauru did shift during the night consistent with the displacement of the island trail. Figure 8 is a MTI (about 13:00 Local Time) daytime image showing the apparent effect of the island in forming bright puffy clouds downwind of the island (west). These clouds seem to eventually develop into a cloud trail in the GMS image. Figure 9 shows the results of analysis of 1 year of GMS satellite images comparing occurrences of island trails with solar radiation and wind speeds measured at the ARM CART. Shelby Winiecki, 2000 performed this work while was a summer student at LANL with the DOE GCEP Program. These results show that both the heating of the island by the sun and the physical interception of the wind may be important at different times.



MTI Thermal Image
1 AM Local Time



GMS Satellite Image 12 hours before nighttime MTI image



GMS Satellite Image 12 hours after nighttime MTI image

Figure 6 Nighttime Thermal IR MTI Satellite Image with GMS satellite images 12 hour before and after.

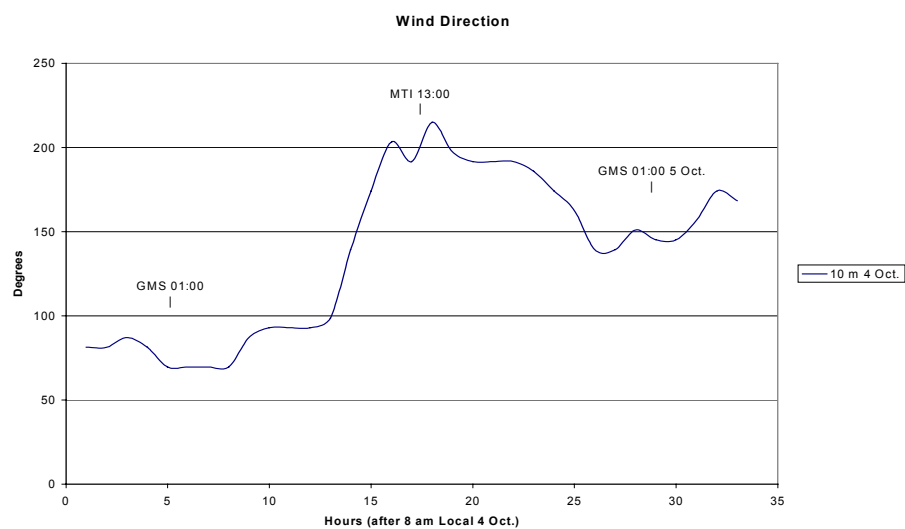


Figure 7 Wind direction measured at ARM CART station in Nauru showing wind shift associated with the island trail

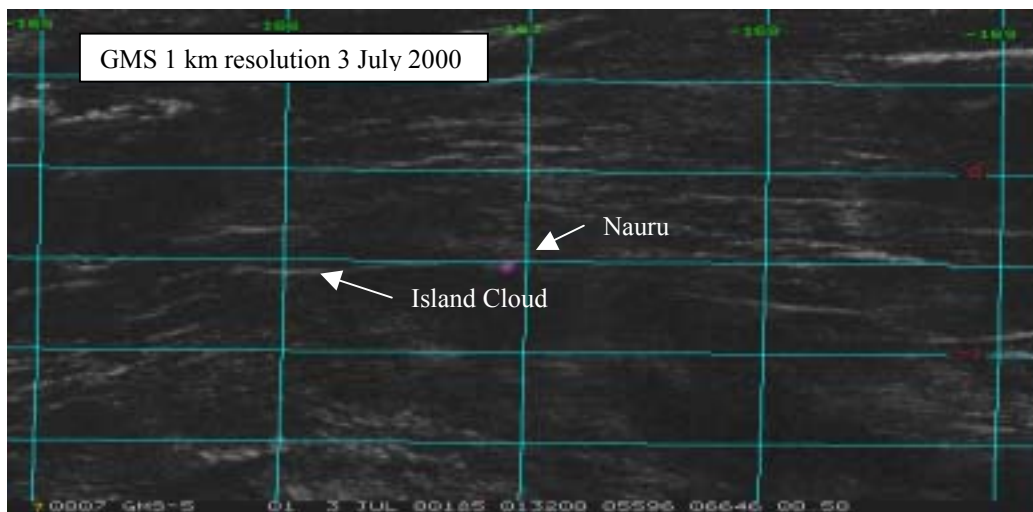
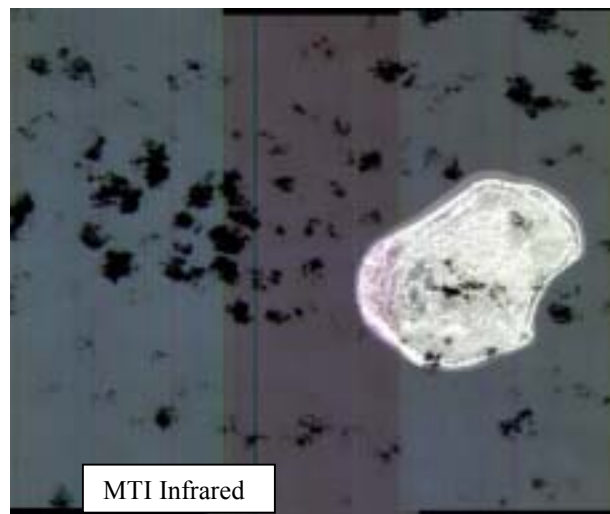


Fig. 8 Daytime (1 PM Local Time) comparison of MTI and GMS satellite images on 3 July 2000

PSP vs Wind Speed

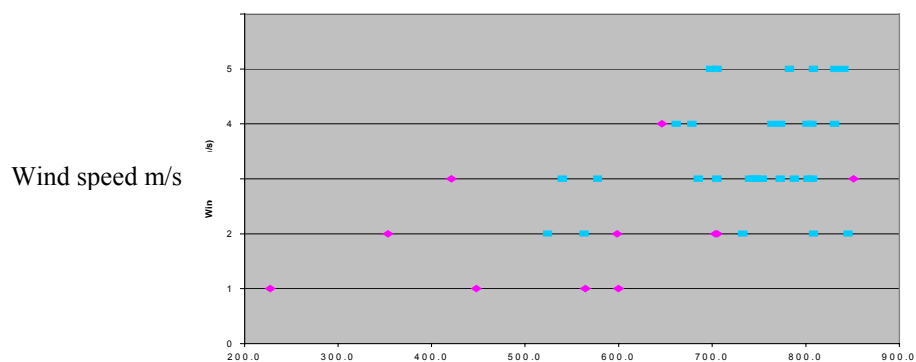


Fig. 9 Occurance (blue) and non-occurance (pink) of Nauru island cloud trail versus solar radiation and wind speed

The island of Nauru was chosen as one of the ground truth comparison sites because of the presence of the ARM CART site, the relatively constant sea surface temperatures, and the high water vapor content. The ground truth analysis is coordinated by the Savannah River Technology Center. For example, at the time the images in Figure 8 were made, we were making surface skin temperature measurements with an infrared thermal sensor and bulk water temperature measurements about 20 cm below the water surface (Figure 10). During Nauru99 ocean surface bulk water temperature measurements were made using a tube called a sea snake. Figure 11 shows that at least for this particular period there was a continuous decrease in ocean surface temperatures downwind of the island of about 0.2 °C. This kind of difference though small may have an effect on island clouds and can be used to test the resolution of the MTI thermal analysis products.



Calibrated infrared temperature sensor for ocean skin temperature (Mal Pendergast SRTC)



Calibrated temperature sensor submerged 20 cm (Bill Kornke LANL)

Fig. 10 Ground truth sea surface and skin temperature measurements on Nauru

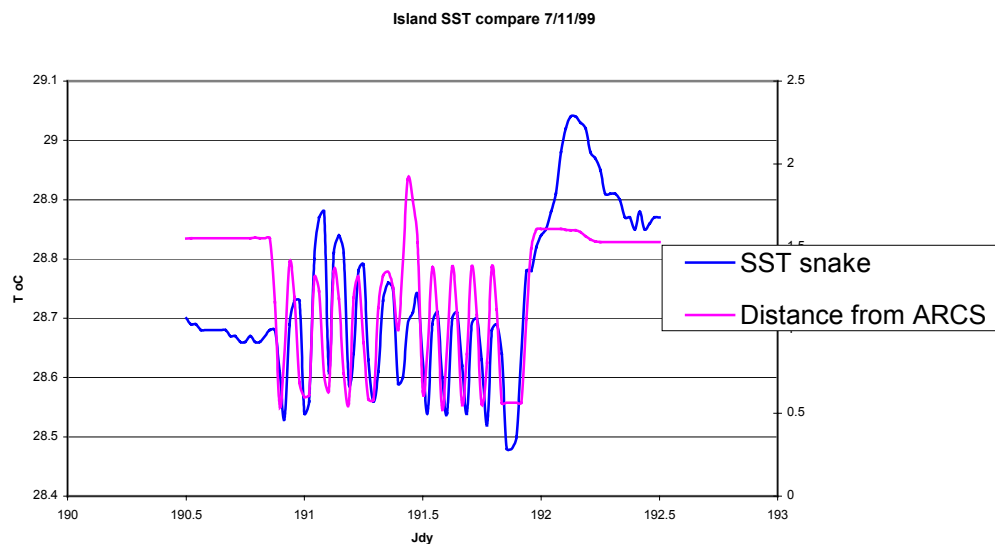


Fig. 11 Sea surface temperature taken as the *RV Ron Brown* circled Nauru for 24 hours plotted as a distance from the ARM CART site on the leeward side of the island showing about 0.2 oC warmer difference on the windward side of the island

Figure 12 shows MTI and GMS satellite images on two days. On Dec. 12, 2000 there are a few puffy clouds downwind of Nauru that do not develop into an island cloud trail. On Dec. 13, 2000 an island cloud develops with clear regions forming on both sides in the background clouds. This very different island effect in just one day represents a good test case for numerical cloud models. The ceilometer data shown in Figure 13 shows that the cloud bottom heights were about 500 m (or less). These relatively low cloud heights and cloud free regions on either side of the island cloud trail are surprisingly similar to ship trail heights and features even though the surface water temperatures are about 15 °C warmer near Nauru than off the Coast of California (about 30 versus 15 °C, respectively).

It was interesting how little difference existed between the two days based on surface measurements. Figure 14 shows that the solar insolation was greater on the 12th (no island cloud) than the 13th (island cloud). This implies that there is more going on than just convective warming by the sun. The wind speeds are slightly higher on the 13th than 12th (about 1 m/s). This would be consistent with higher turbulence generated by the physical interception of the wind by the island. However, the small difference in wind speeds doesn't seem sufficient to explain the difference. The atmospheric pressure dropped by about 1 hPa on the 13th. The surface relative humidity was almost the same on the two days, and the surface temperature was about 1 °C warmer on the 13th. The column integrated precipitable water vapor measured by the microwave radiometer was lower on the 13th than the 12th by about 0.3 cm.

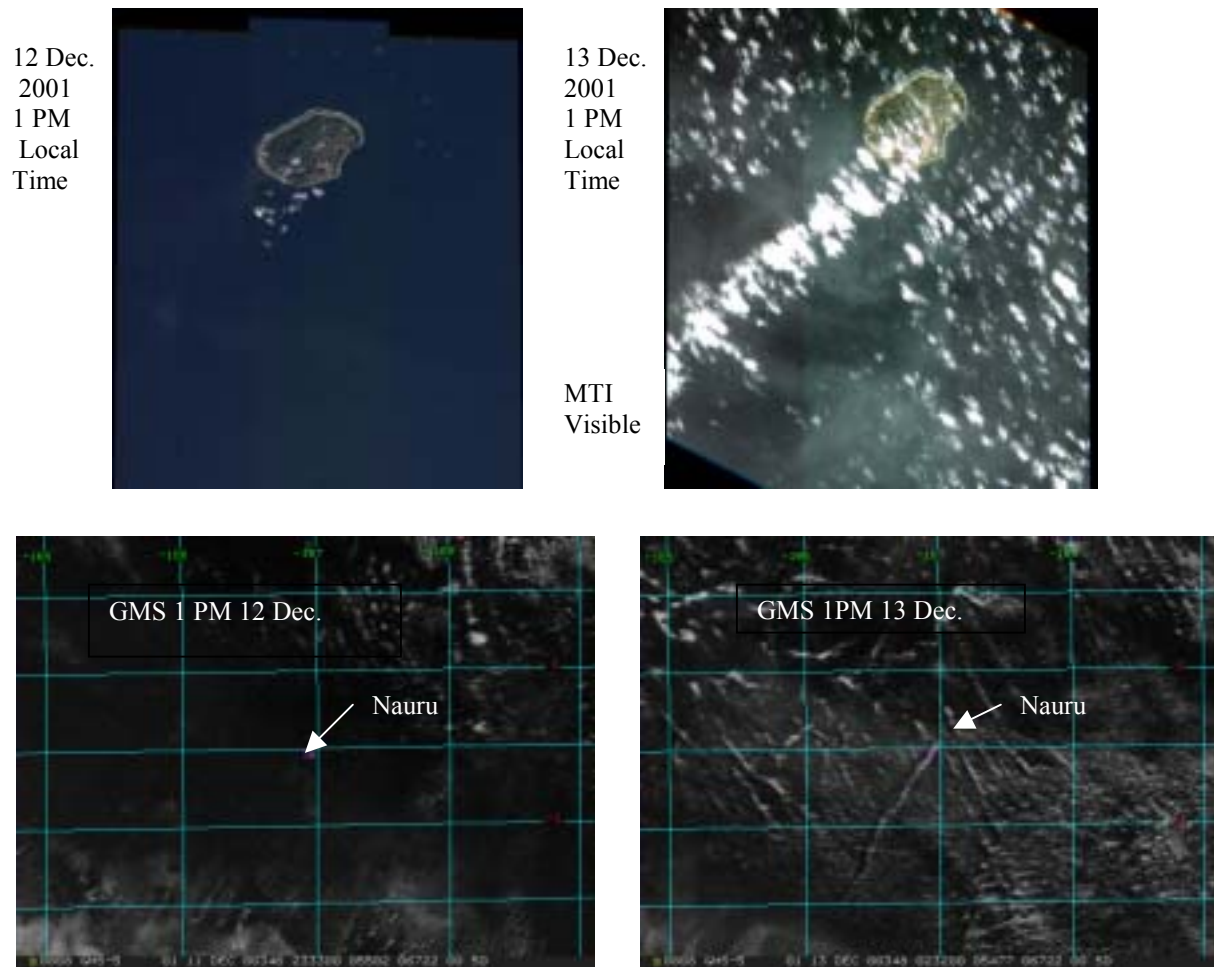


Fig. 12 Comparison of MTI (visible) and GMS images on 12 Dec. (no island cloud trail) and 13 Dec., 2000 (with cloud trail)

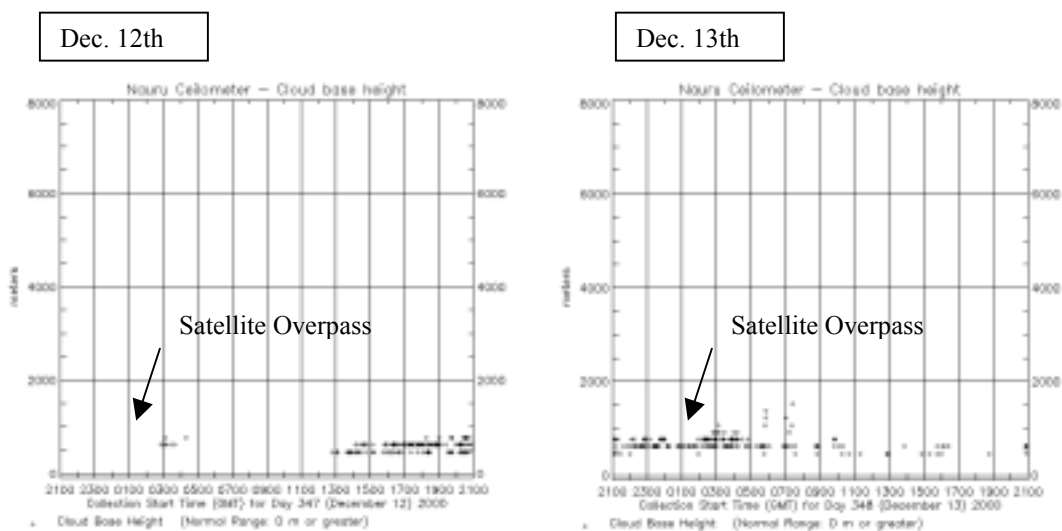


Fig. 13 Ceilometer data for two days shown in Fig. 12 showing cloud bottom heights of 400 to 600 m

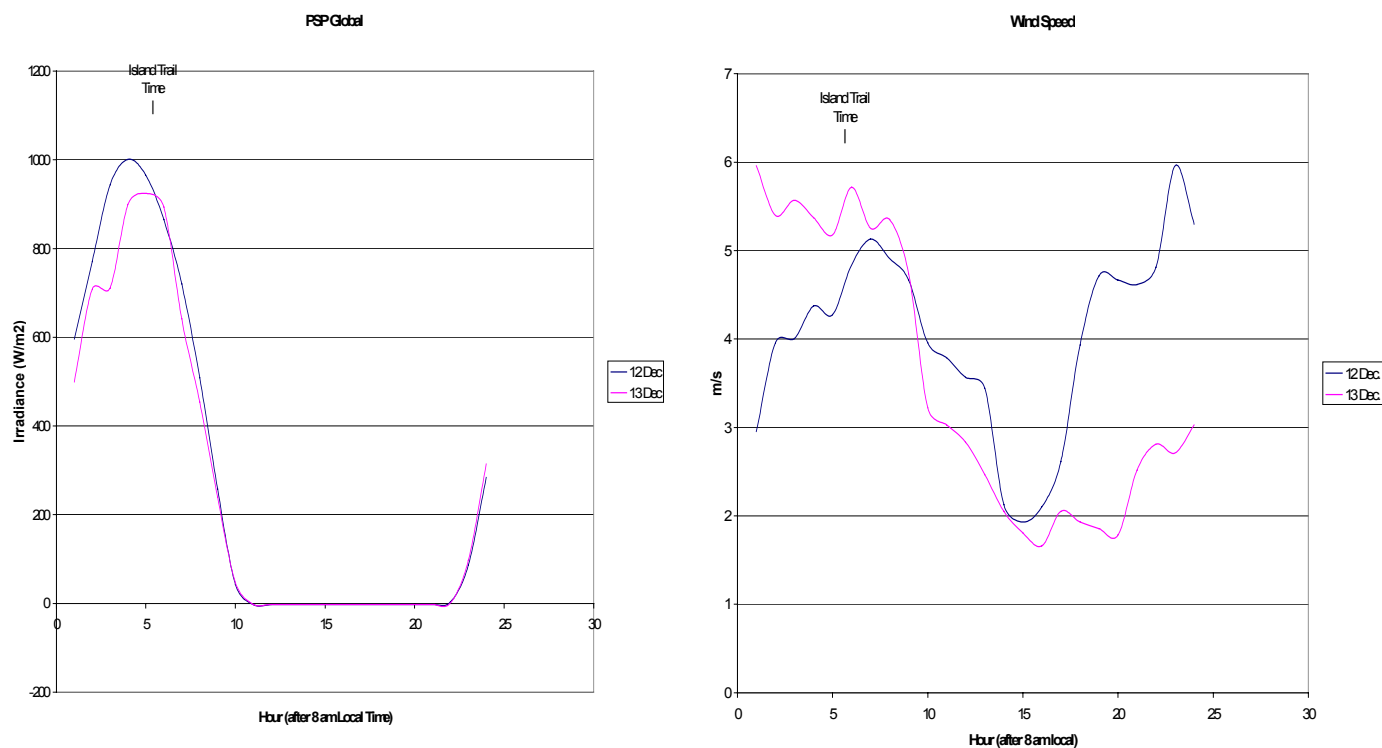


Fig. 14 Global solar radiation (left) and wind speeds (right) measured at the ARM CART site at Nauru on the 12th (no island trail – blue) and the 13th (island trail – pink)

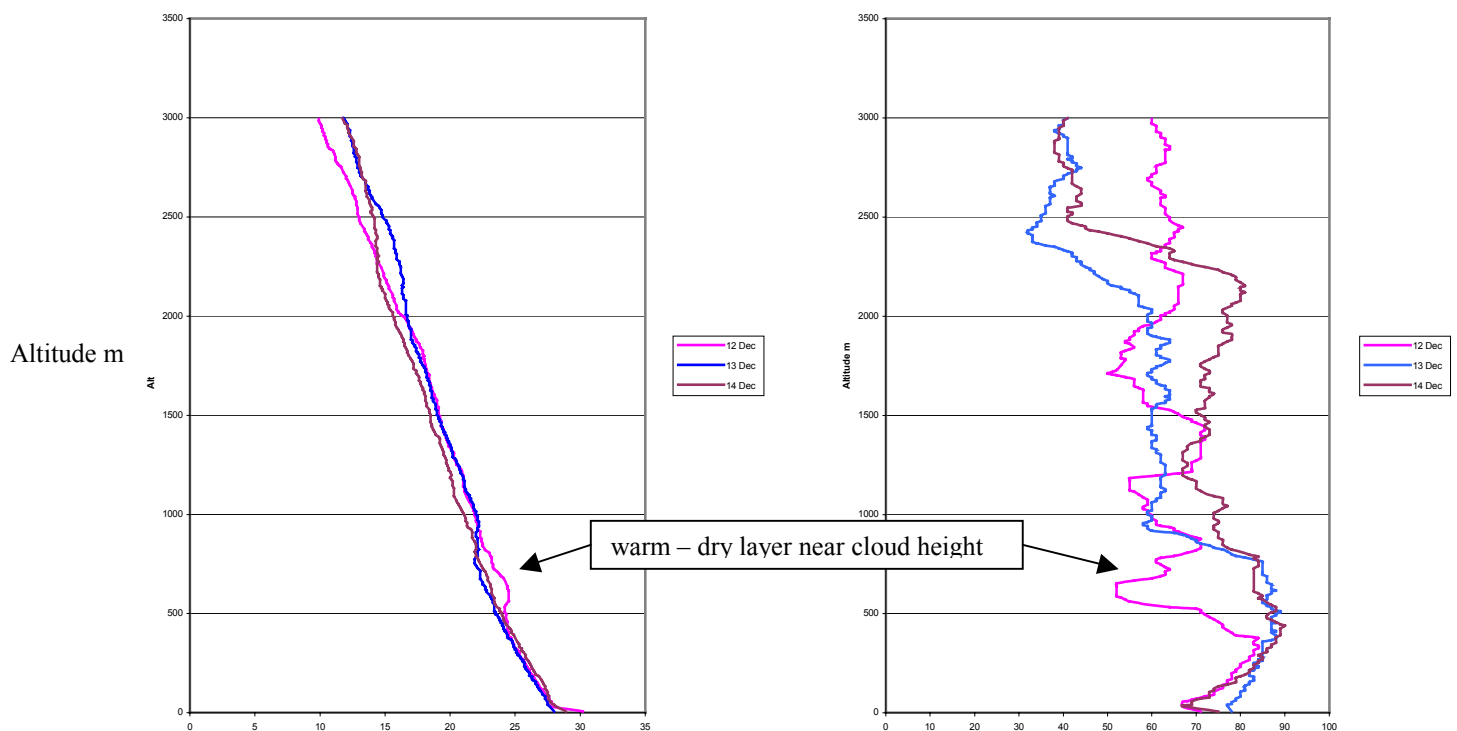


Fig 15 vertical profiles of temperature (left) and relative humidity (right) for the 12th (no island trail – pink), the 13th (island trail – blue), and 14th (following day – brown).

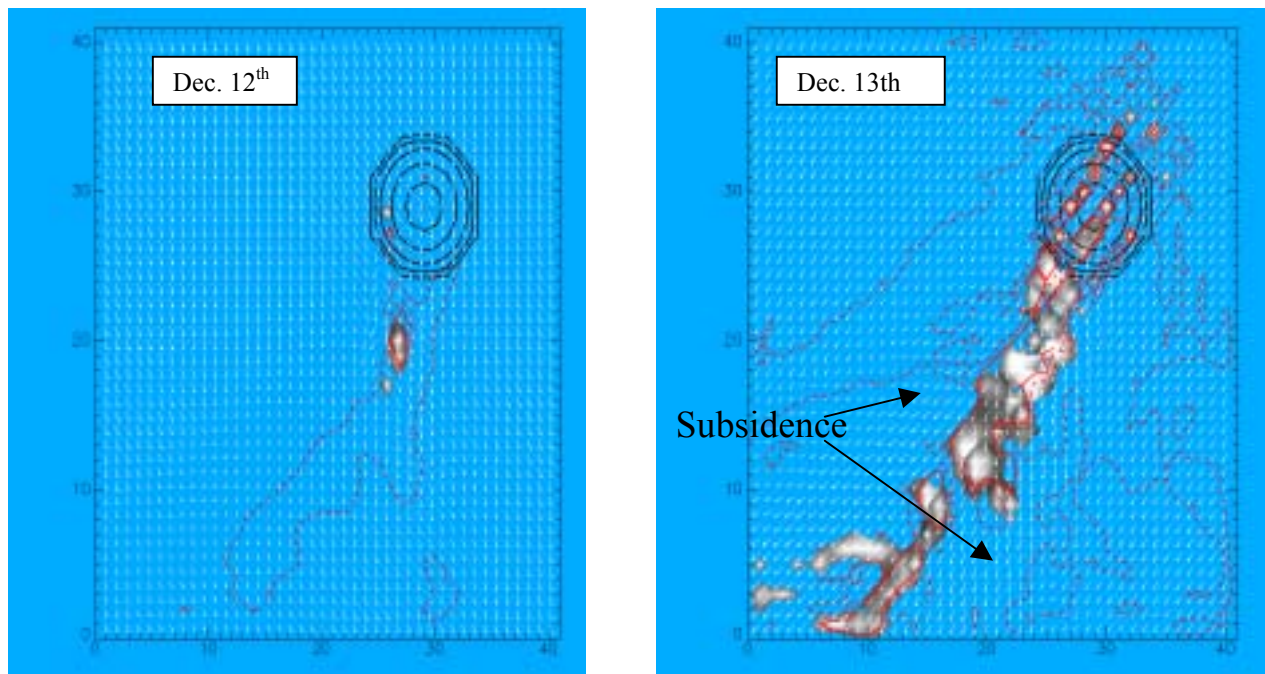


Fig. 16 Numerical cloud model (RAMS) simulation using the profiles in Fig. 15 for the 12th (no island trail – left) and 13th (island trail – right) using only physical island approximations (no aerosol CCN microphysics)

The atmospheric profiles of temperature and water vapor from the rawinsonde launched about 1 hour before the satellite images show the critical difference between the two days. Figure 15 shows the rawinsonde profiles for the 12th as a pink line, and 13th as a blue line (also the 14th brown). This shows a warm dry layer on the 12th just above 500 m that inhibited cloud formation on the 12th.

These profiles were used as input into a predictive cloud model (RAMS). The model was configured with two grids. The outer grid was 80 km x 80 km with 2 km grid spacing. The inner grid was 20 km x 20 km with 500m grid spacing. The vertical grid spacing for both grids telescoped vertically with a grid spacing of 20m at the surface. Vertical turbulent diffusion was computed from the Mellor-Yamada scheme; horizontal diffusion was deformation based. Bulk microphysics was activated with diagnostic computation of cloud water and raindrop concentrations. For these simulations the island topography was idealized with a maximum elevation of 40m at the center and falling off as the square root of the distance from the center. The area of the idealized island was approximately the same as Nauru. Default values of albedo and roughness height for a semi-desert vegetation type and sandy soil type were utilized. Figure 16 shows the results of the simulation with a remarkable agreement between the form of the clouds developed on the 12th and 13th.

THE DICHOTOMY:

- Island cloud trails seem to be explained by boundary layer cloud dynamic effects.
- Ship trail clouds are usually explained as a result of ship smoke aerosol (indirect aerosol cloud effect).

A sub-problem related to this dichotomy is that ocean clouds can be starved for both CCN and turbulence. We participated in a relatively large ocean experiment developed by the Office of Naval Research to try to improve our understanding of the role of aerosols in ship track formation and hopefully to resolve this dichotomy (preview: we didn't resolve this conflict).

MAST 1996:

Multiple observations made from a small research vessel (*R/V Glorita*) during the Monterey Area Ship Tracks (MAST) experiment in June 1994 were combined to describe the physical and dynamic characteristics of ship-track clouds (Porch *et al*, 1999). A wide variety of aerosol and meteorological parameters were measured from the *R/V Glorita* simultaneous with aircraft flights. The focus of the surface, airborne and satellite studies was to understand better the relative importance of aerosol microphysical effects and cloud dynamic processes in the formation and maintenance of ship tracks (MAST 1994). The focus of the surface studies during MAST was to improve the characterization of aerosol microphysical properties and cloud dynamic processes in ship tracks (MAST, 1994). Important measurements were made during the MAST experiment from the *R/V Glorita*. Vertical profiles of background meteorological parameters (needed as input to numerical models simulating ship tracks) were obtained from both rawinsonde and tethered balloons launched from the *R/V Glorita* (Syrett 1994). Also, surface properties such as sea surface temperatures, heat and moisture fluxes, were obtained from measurements on the ship.

Surface aerosol properties and lidar measurements of the interaction of ship plumes and marine boundary layer clouds were made from the ship (Hooper and James, 2000). Measurements of cloud bottom heights related to ship-track clouds were measured from the ship with commercial ceilometers. . We also developed a small battery-operated continuous-wave Doppler Radar system with a frequency of 35 GHz that was gimbaled to compensate partially for ship motions. This system provided only integrated velocity and return signal analysis. Passive remote sensing instruments included a microwave radiometer MWR (used to determine vertically integrated water vapor and cloud liquid water content), two pyranometers, and a pygeometer. A whole-sky camera and time-lapse video system provided a continuous record of cloud cover during the day.

MAST RESULTS:

Because of constant high winds and logistical difficulties we were unable to sample cloud droplet sizes with height using our tethered balloon system. We were able to observe cloud dynamic effects associated with ship tracks using remote sensing systems. Figure 17 shows the backscattering intensity with altitude using data from the ceilometer. In most cases the clouds were thick enough to extinguish the laser light so the cloud bottom heights (lower transition to white) are representative while the top of the white layer is usually not the top of the cloud. The three days of ceilometer data shown in Figure 17 show cloud bottom morphology that appears to be related to the passing of a ship tracks observed by satellite (6/12 and 6/27) and ship affected clouds where no ship track was observed but the ship plume was detected from CN measurements (6/28). The cloud bottom heights appear lower as the ship affected clouds passed over on 6/12 and 6/27. In these cases the ship affecting the clouds were closer than 20 km. One of the ship track cases on 6/12 was accompanied by clear regions on each side as shown in the pyranometer measurements included in Figure 18. On 6/27 the ship tracks that passed the *Glorita* were considerably older (Figure 18). In this case the clouds appear slightly elevated in the ship track above the background clouds. This is consistent with modeling results (Porch and Kao, 1996) that predict that dynamic effects will cause ship tracks to lift slowly with time. The case on 6/12 that did not show clear regions on each side on the ship affected cloud did show a thinning effect in the pyranometer data accompanied with regions of slight subsidence on each side of the track observed with the 35 GHz Doppler CW Radar (Figure 19). All of these observations indicate a cloud dynamic effect.

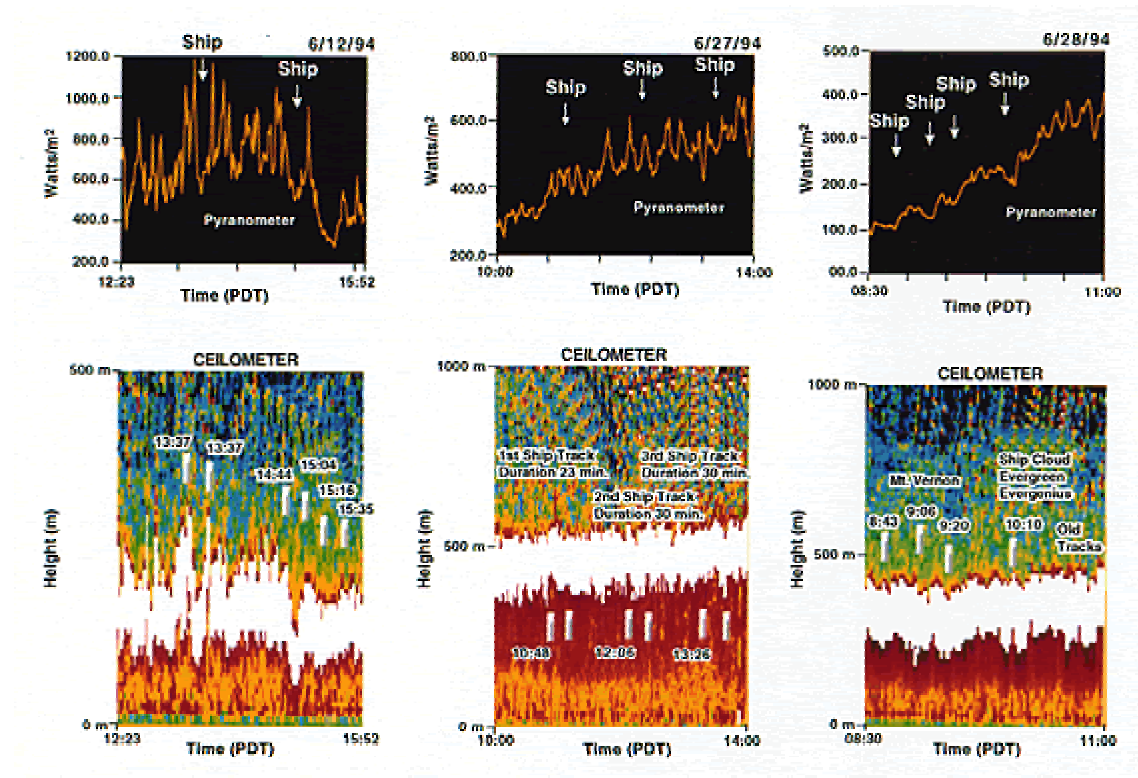


Fig. 17 Ceilometer backscattering intensity showing cloud bottom heights apparently affected by ship tracks and ship affected clouds

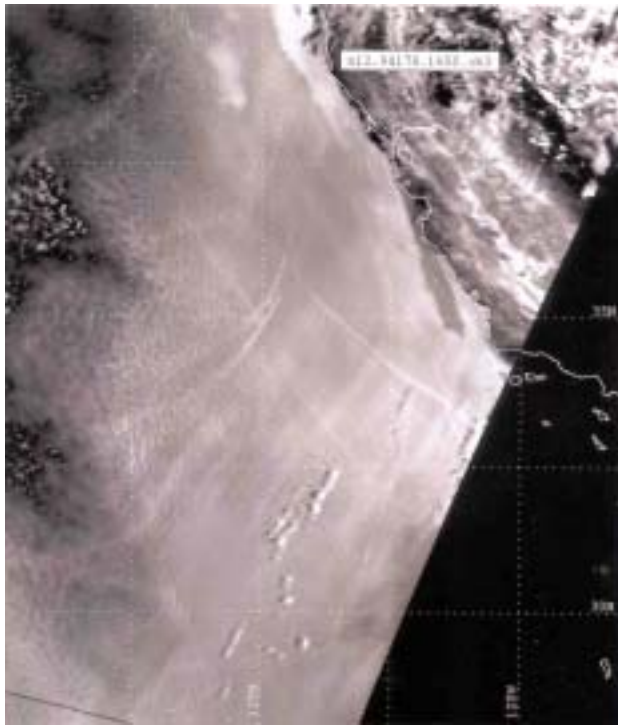


Fig. 18 Ship Tracks observed from channel 3 of the NOAA AVHRR satellite during MAST on 6/27/94

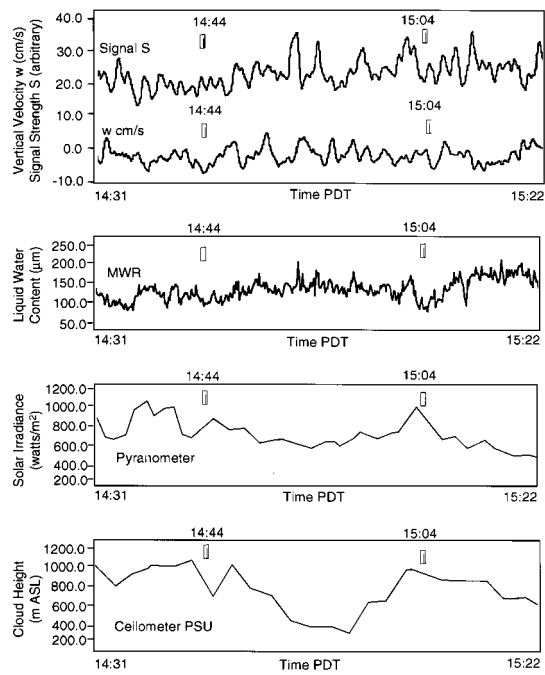


Fig. 19 Doppler Radar CW 35 GHz verticle winds, microwave radiometer cloud liquid water, solar radiation, and ceilometer cloud bottom heights during ship trail overpass on 12 June 1994

These cloud dynamic observations contrast somewhat with the conclusion of the MAST study (Durkee et al, 2000):

“Statistics and case studies, combined with model simulations, show that provided a cloud layer is susceptible to an aerosol perturbation, and the atmospheric stability enables aerosol to be mixed throughout the boundary layer, the direct emissions of cloud condensation nuclei from the stack of a diesel-powered ship is the most likely, if not the only, cause of the formation of ship tracks.”

The observations that supported this conclusion were based on satellite observations and aircraft CCN and cloud droplet sampling through ship tracks. Table 1 summarizes the observations that support the importance of CCN in ship track formation (including caveats that modify the strength of the observation connection). Table 2 summarizes the observations that support a cloud dynamic explanation of ship track formation (also including caveats).

Figure 20 illustrates how possible differences of cloud droplet size with height could confuse an aircraft sample pass into producing results that might be interpreted as showing that ship trail cloud droplets are smaller than those in background clouds. If the ship track cloud is higher than the background cloud, evaporation of the drops near the top may also explain why the satellite observations at wavelengths close to 3 micrometers may show more contrast than visible wavelengths. We were unsuccessful during MAST in measuring vertical droplet size profiles in ship trail clouds and background clouds.

Though the evidence is substantial suggesting that aerosol is important in most ship trail cloud formation, it is not overwhelming. It is also possible that CCN nucleation might induce dynamic effects through latent heat of condensation release in the nucleation process. This is consistent with higher levels of cloud liquid water content often observed in ship trail clouds. This, of course, is a very different explanation for the higher liquid water content than drizzle suppression caused by CCN making the droplets smaller (Albrecht, 1989).

Table 1 Evidence Supporting an Aerosol Mechanism for Ship Trail Cloud Formation

	Caveats
Ship Tracks are usually more visible at near IR wavelengths (about 3 microns)	Dynamic effects may also make cloud drops smaller at the top of ship track clouds especially if the top extends higher into warmer region above the background clouds
Droplet sizes measured by aircraft are often smaller in ship tracks	Droplet sizes may be different with height in a ship track cloud than background clouds
Ship tracks were not observed in clouds with droplet concentrations more than about 100 drops / cm ³	Other variables such as boundary layer height and age of the cloud may be associated with high droplet concentrations and also inhibit cloud track formation
Our little research vessel (Egabrag) made a ship track	Though our ship put out high CCN concentrations and low buoyant heat, it did produce turbulence by intercepting the high winds

Table 2 Evidence Supporting a Dynamic Mechanism for Ship Trail Formation

	Caveats
Cloud free regions are often observed on ship trail cloud sides	Most ship trail clouds do not show cloud free regions on the sides
Ship trail clouds were not observed when the cloud bottom heights were above 600 m even though the atmosphere was well mixed and CCN should be mixed into the clouds	We have relatively few measurements of ship tracks observed simultaneously with cloud height (about 20)
Cloud top and bottom heights are different in ship trail clouds than the background clouds	We have only two observations of higher cloud top heights and maybe 5 observations of cloud bottom differences
No excess sulfate was found in ship track droplets	Some other chemical might be active in cloud formation or there was a sampling problem
Region where two ship tracks intersect appears no brighter than the nonintersecting elements of the trail	There may be a saturation effect in that a little CCN make the cloud brighter but more doesn't help

CONCLUSIONS:

- 10 years of ship trail cloud studies indicate both aerosol and dynamic effects (more work is needed to separate them)
- Island cloud trails seem to be explained by dynamic effects and more research on these effects may prove useful in understanding how boundary layer clouds respond to climate changes

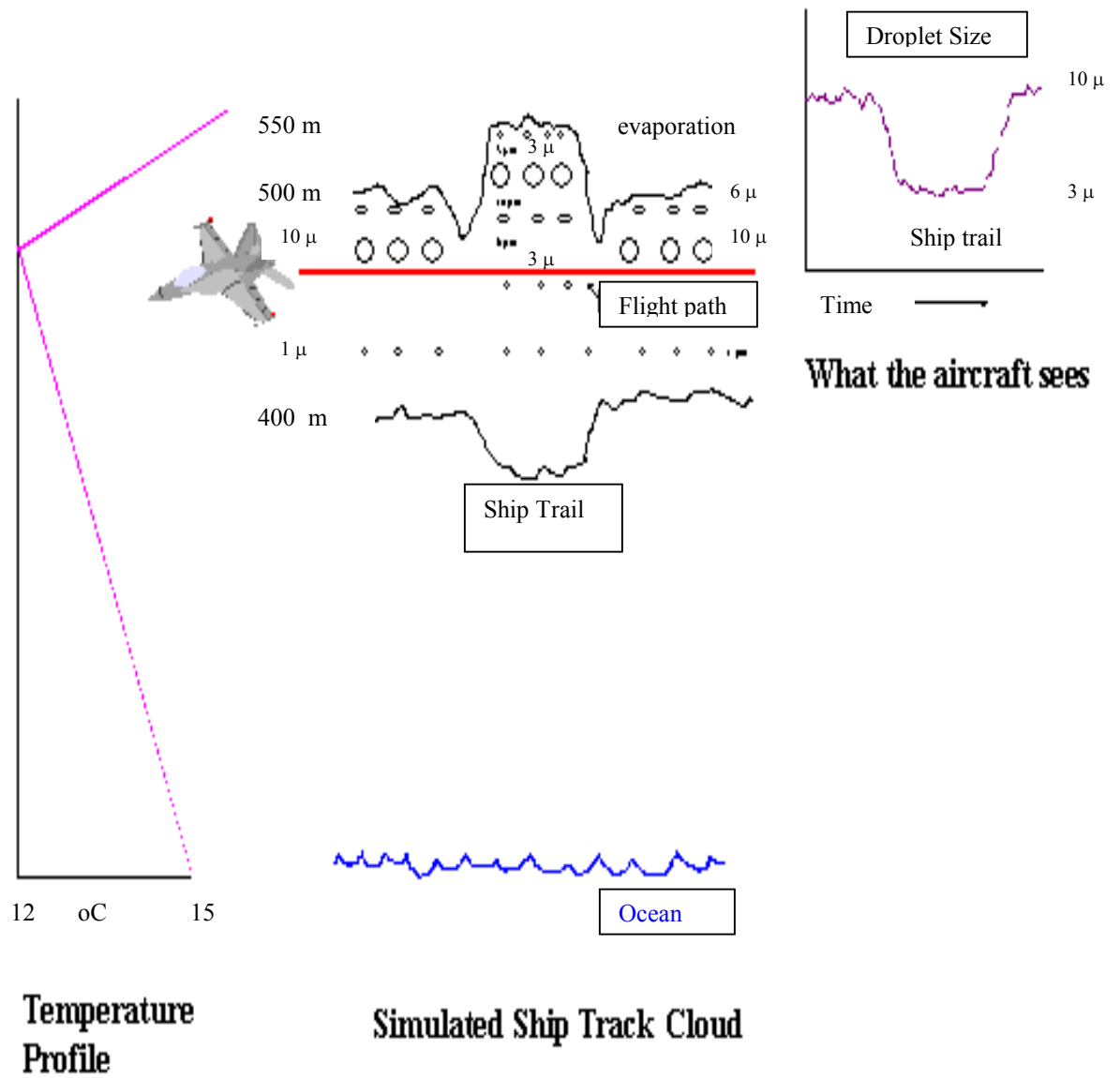


Fig 20 Illustration of how a difference in cloud droplet size in the verticle and a ship trail cloud top higher than the background clouds could make an airplane sample see smaller drops within the ship trail cloud and satellite see smaller drops at ship trail cloud top

ACKNOWLEDGMENTS:

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